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# TECHNICAL MEMORANDUM

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EXPERIMENTAL INVESTIGATION OF THE PARTIAL-ADMISSION PERFORMANCE CHARACTERISTICS OF A SINGLE-STAGE MACH 2 SUPERSONIC TURBINE

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# EXPERIMENTAL INVESTIGATION OF THE PARTIAL-ADMISSION PERFORMANCE CHARACTERISTICS OF A SINGLE-STAGE MACH 2 SUPERSONIC TURBINE*

By Thomas P. Moffitt and Frederick W. Klag, Jr.

## SUMMARY

The experimental investigation of the partial-admission performance characteristics of a single-stage supersonic turbine is presented. A range of admissions from full-admission to 12.5-percent admission was covered.

At full admission the equivalent specific work output obtained at design speed and pressure ratio was 33.0 Btu per pound at a static efficiency of 0.425. For all other admissions, no significant effect on performance was noted for either design or off-design conditions of operation.

The results were in good agreement with predicted performance based on an analytical reference. At 12.5-percent admission the prediction method used indicated a drop in expected over-all static efficiency of about 5 percent for the subject turbine.

## INTRODUCTION

In many applications of turbine-driven equipment, such as turbopumps and electric power supplies, there exists a desire for minimum turbine flow rates and high specific work outputs. This is particularly true in missile and space applications where the ratio of payload to gross weight must be kept as high as possible. If high specific work outputs are used in applications of low power levels, the required flow rate can be so low that the resulting blade height for full admission would be prohibitively small and attendant viscous losses would become severe.

One way of retaining desirable blade heights while operating at low flow rates is through the use of partial admission. This is a system in

*Title, Unclassified.

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which the required flow is passed through a certain percentage of the turbine nozzle annulus. Thus, this system utilizes larger blade heights than full admission and also serves as a means of decreasing viscous losses.

There are, however, performance penalties specifically attendant to the use of partial admission. They arise from two sources: (1) unsteady or periodic filling and emptying of the rotor blades as they pass the admitted nozzle arc, termed a momentum exchange loss, and (2) the pumping of relatively stagnant fluid in the portion of the rotor blade annulus that is unadmitted. These penalties are in addition to the normal aerodynamic losses as well as friction and bearing losses, which can become a significant percentage of the output power at very low power levels. The partial-admission losses have been studied analytically for impulse blading in reference 1, which defines the losses as functions of the number of rotor blades in the admitted stator arc and the blade - jet speed ratio. Some data are presented in reference 1, however, very little data are available to corroborate the results shown, particularly in the supersonic turbine range, which is an area of current interest and well suited to the use of partial admission (ref. 1).

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An investigation was therefore conducted at the NASA Lewis Research Center to obtain the performance characteristics of an existing single-stage supersonic turbine, the full-admission performance of which is presented in reference 2. This turbine, having a rotor-inlet relative Mach number of 2 and blade-jet speed ratio of 0.174, was modified for the partial-admission investigation. The arc of admission was varied from 100 to 12.5 percent admission; the 12.5 percent arc of admission was the lowest at which data could be obtained.

This report presents the results of this investigation and compares them with analytical performance characteristics based on reference 1.

## SYMBOLS

$a$ active nozzle arc length, ft

$\Delta h'$ specific work output, Btu/lb

$M$ Mach number

$p$ absolute pressure, lb/sq ft

$s$ rotor-blade spacing, ft

$U$ mean section blade speed, ft/sec

| | |
|---|---|
| $V$ | absolute gas velocity, ft/sec |
| $V_j$ | ideal velocity corresponding to the pressure ratio, $p_2/p_0'$ |
| $w$ | weight-flow rate, lb/sec |
| $\gamma$ | ratio of specific heats |
| $\delta$ | ratio of inlet air total pressure to NASA standard sea-level pressure, $p_0'/p^*$ |
| $\varepsilon$ | function of $\gamma$, $\frac{\gamma^*}{\gamma}\left[\frac{\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma}{\gamma-1}}}{\left(\frac{\gamma^*+1}{2}\right)^{\frac{\gamma^*}{\gamma^*-1}}}\right]$ |
| $\eta$ | static efficiency, based on ratio of static- to total-pressure across turbine, $p_2/p_0'$ |
| $\theta_{cr}$ | squared ratio of critical velocity at turbine inlet to critical velocity at NASA standard sea-level temperature, $(V_{cr,0}/V_{cr}^*)^2$ |



Subscripts:

| | |
|---|---|
| cr | conditions at Mach number of 1.0 |
| f | full-admission |
| p | partial-admission |
| R | relative to rotor blade |
| x | axial component |
| 0 | turbine inlet |
| 1 | stator exit, also rotor inlet |
| 2 | turbine outlet |

Superscripts:

| | |
|---|---|
| ' | absolute total state |
| * | NASA standard conditions |

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## TURBINE CONFIGURATION

The turbine used in this experimental investigation is the same as that described in reference 2. The turbine design parameters were:

Mean section blade speed, $\frac{U}{\sqrt{\theta_{cr}}}$, ft/sec . . . . . . . . . . . . . . . . 342

Pressure ratio, $\frac{p_2}{p_0'}$ . . . . . . . . . . . . . . . . . . . . . . . . . 0.033

Weight flow, $\frac{\varepsilon w \sqrt{\theta_{cr}}}{\delta}$, lb/sec . . . . . . . . . . . . . . . . . . . . 0.585

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The selection of these parameters resulted in a blade-jet speed ratio $\frac{U}{V_j}$ of 0.174. For these design conditions at full admission the turbine achieved a static efficiency of 0.414, as reported in reference 2.

The design velocity diagrams together with a sketch of the blade profiles and flow passages indicating the station nomenclature are shown in figure 1, in which it can be noted that:

(1) $M_R = 2$ at the rotor inlet

(2) Approximate impulse conditions exist across the rotor as $M_R$ increases from 2.0 at the inlet to 2.1 at the exit

(3) The stator convergent section accomplishes the required turning of the flow (72.6°) with the divergent section representing the minimum expansion passage length capable of delivering uniform shock-free exit flow

(4) There is high turning (137°) of the flow in the rotor

Figure 2 shows a photograph of the rotor. The mean blade diameter was 10.3 inches and the hub-tip radius ratio was 0.9 at the rotor inlet with the blade height (nominal 1/2 in.) increased to a hub-tip radius ratio of 0.87 at the rotor outlet.

Figure 3 presents a sketch of the turbine showing the curved metal blockage pieces that were used to obtain partial admission. This sketch also indicates how the pieces were modified to vary the arc of admission. The nozzles were blocked both at the inlets and exits and the downstream blockage piece was tapered appropriately to form a smooth stator exit. Since there were 32 stator blades it was convenient to obtain a systematic reduction in arc of admission by blocking off even increments of blades. The following table illustrates the schedule observed:

| Configuration | Arc, percent | Active nozzles | a/s |
|---|---|---|---|
| 1 | 100 | 32 | 48 |
| 2 | 75 | 24 | 36 |
| 3 | 50 | 16 | 24 |
| 4 | 25 | 8 | 12 |
| 5 | 12.5 | 4 | 6 |

## APPARATUS, INSTRUMENTATION, AND PROCEDURE

The turbine tests were conducted in the facility described in reference 2. A cradled dynamometer was used to absorb the turbine power output. Figure 4 presents a diagrammatic sketch of the turbine test rig. (This configuration is basically the same as the full-admission configuration and therefore fig. 4 is taken from ref. 2.) Low-friction shaft bearings were used so that the bearing losses were low compared with the power level at least down to the lowest percentage of admission reported. Thus, this effect was not considered in the performance calculations and it was assumed that the aerodynamic turbine efficiency was equal to the turbine power efficiency.

The instrumentation used to obtain the over-all turbine performance is essentially the same as that used for the experimental program described in reference 2. Pressures and temperatures were obtained for both turbine-inlet (station 0, fig. 4) and -exit (station 2, fig. 4) conditions. The actual specific work output was computed from measurements of torque, speed, and weight flow. The torque was measured with a commercial, self-balancing torque cell and manometer, and the speed was measured with an electronic events-per-unit-time meter. The full-admission weight flow was measured with a calibrated ASME orifice. However, at the low arcs of admission the orifice was unable to measure the flow accurately. Therefore, the values of weight flow for use in calculations were obtained in the following manner: All throat areas were measured and indexed; then, for a given percentage of admission, the combined areas of the unblocked nozzles were ratioed to the total nozzle area and this portion of the full-admission weight flow was used as the partial-admission weight flow.

The experimental procedure consisted of five performance runs covering the arcs of admission previously described. The turbine was run at constant nominal inlet pressure of 75 pounds per square inch absolute and temperature of 200° F. For each of the arcs of admission investigated, tests were run at constant speeds of 20, 40, 60, 80, and 100 percent of design speed. Also, for each arc of admission and speed investigated, the ratio of static to total pressure across the turbine was varied from approximately 0.5 to the minimum obtainable, about 0.03.

## RESULTS AND DISCUSSION

### Over-All Turbine Performance

The effect of partial admission on turbine performance is shown in figure 5. Equivalent specific work output is shown as a function of over-all pressure ratio for selected values of percentage of design speed and percentage of arc of admission. Because of the quantity and proximity of data points, only one averaging curve was drawn for each speed investigated.

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The equivalent specific work output obtained at full admission and design operating speed and pressure ratio was 33.0 Btu per pound. The design point performance remained constant within the accuracy of the instrumentation over the entire range of admissions considered. This was also true for the complete range of off-design operating conditions, as evident from figure 5. The only data points that did not fall on or near the averaging curves were those for 25-percent admission and at low pressure ratios. These points, however, are felt to be within the experimental accuracy of torque, pressure, and weight-flow measurements.

The variation in static efficiency at design pressure ratio is shown in figure 6. Efficiency is shown as a function of percentage of admission for selected values of percentage of design speed at the design over-all pressure ratio $p_2/p_0'$ of 0.033. It is noted from figure 6 that, for the range of admissions considered, very little effect on turbine efficiency was encountered because of partial admission. The efficiency ranged from 0.425 at design speed down to 0.105 at 20 percent of design speed.

### Comparison with Predicted Performance

A method of analytically predicting the partial-admission performance is presented in reference 1. The penalty in turbine efficiency due to partial-admission losses is derived as a function of magnitude of admission. The parameter $a/s$ used in reference 1 to describe the magnitude of admission, is defined as the ratio of active nozzle-arc length, which varies with admission, to rotor-blade spacing, a constant for a given turbine.

The method includes two aerodynamic losses attributable to partial admission. The first is a loss in momentum due to filling and emptying the rotor-blade passages as they enter and leave the active nozzle arc.

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The second is a pumping loss due to the energy required to carry the stagnant fluid around the inactive portion of the blade annulus. An equation is derived in reference 1 (eq. (D.11)) that relates the magnitude of these losses to the turbine design characteristics. This equation was applied to the design characteristics of the subject turbine and resulted in the predicted performance curve shown in figure 7.

The ordinate of figure 7 shows turbine performance as the ratio of partial-admission efficiency to full-admission efficiency. The abscissa is the previously described parameter, a/s, used in reference 1 to show the magnitude of admission. A second abscissa is also shown that represents the corresponding percentage of arc of admission for the subject turbine.

The prediction curve is nearly flat over a wide range of admission and shows an expected decrease in performance of about 5 percent as the admission is decreased to 12.5 percent. In fact, it would be expected from the curve (fig. 7) that performance would not be penalized more than 10 percent until the arc of admission was decreased to values less than 7 percent. For admissions less than this, the expected performance drops off very rapidly until a point would be reached where the turbine work output would equal the pumping and bearing losses. Beyond this point, design speed could no longer be obtained.

The average experimental performance of the subject turbine is shown in figure 7 as a dashed line at a value of $\eta_p/\eta_f$ of 1.0. As discussed previously, partial admission had no significant effect on turbine performance at either design or off-design conditions of operation. This is in good agreement with the prediction curve of figure 7 over the range of admission covered.

The results of this investigation are compatible with one of the conclusions in reference 1, which states that low velocity ratio (blade-jet speed ratio) turbines are especially adaptable to partial-admission applications. These turbines can be run over a wide range of admission with only small penalties in performance.

## SUMMARY OF RESULTS

The experimental investigation of the partial-admission performance characteristics of a single-stage supersonic turbine has been made. A range of admissions from 100 to 12.5 percent admission was covered. The results can be summarized as follows:

1. At full-admission, the equivalent specific work output obtained at design speed and pressure ratio was 33.0 Btu per pound at a static efficiency of 0.425. For all admissions down to 12.5 percent, no

[redacted]

significant effect on performance was noted for either design or off-design conditions of operation.

2. The results were in good agreement with predicted performance based on an analytical reference. This reference predicted only a small penalty in performance over the range of admissions considered. At 12.5 percent admission, the prediction method used indicated a drop in expected over-all static efficiency of about 5 percent for the subject turbine. A penalty of 10 percent would not be expected until the admission was decreased to values less than 7 percent of full admission.

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Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, June 4, 1959

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2. Moffitt, Thomas P.: Design and Experimental Investigation of a Single-Stage Turbine with a Rotor Entering Relative Mach Number of 2. NACA RM E58F20a, 1958.

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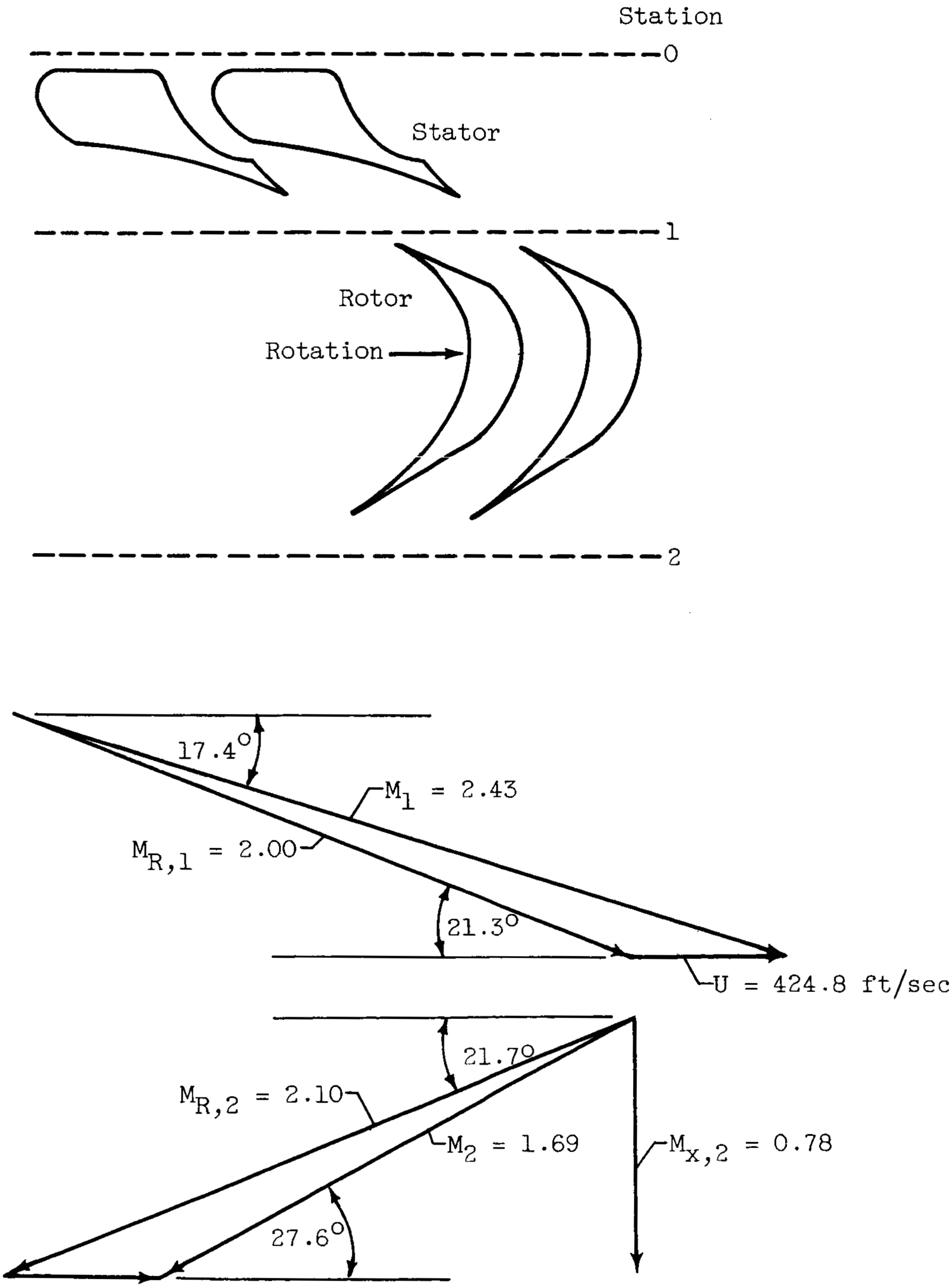


Figure 1. - Design velocity diagrams.

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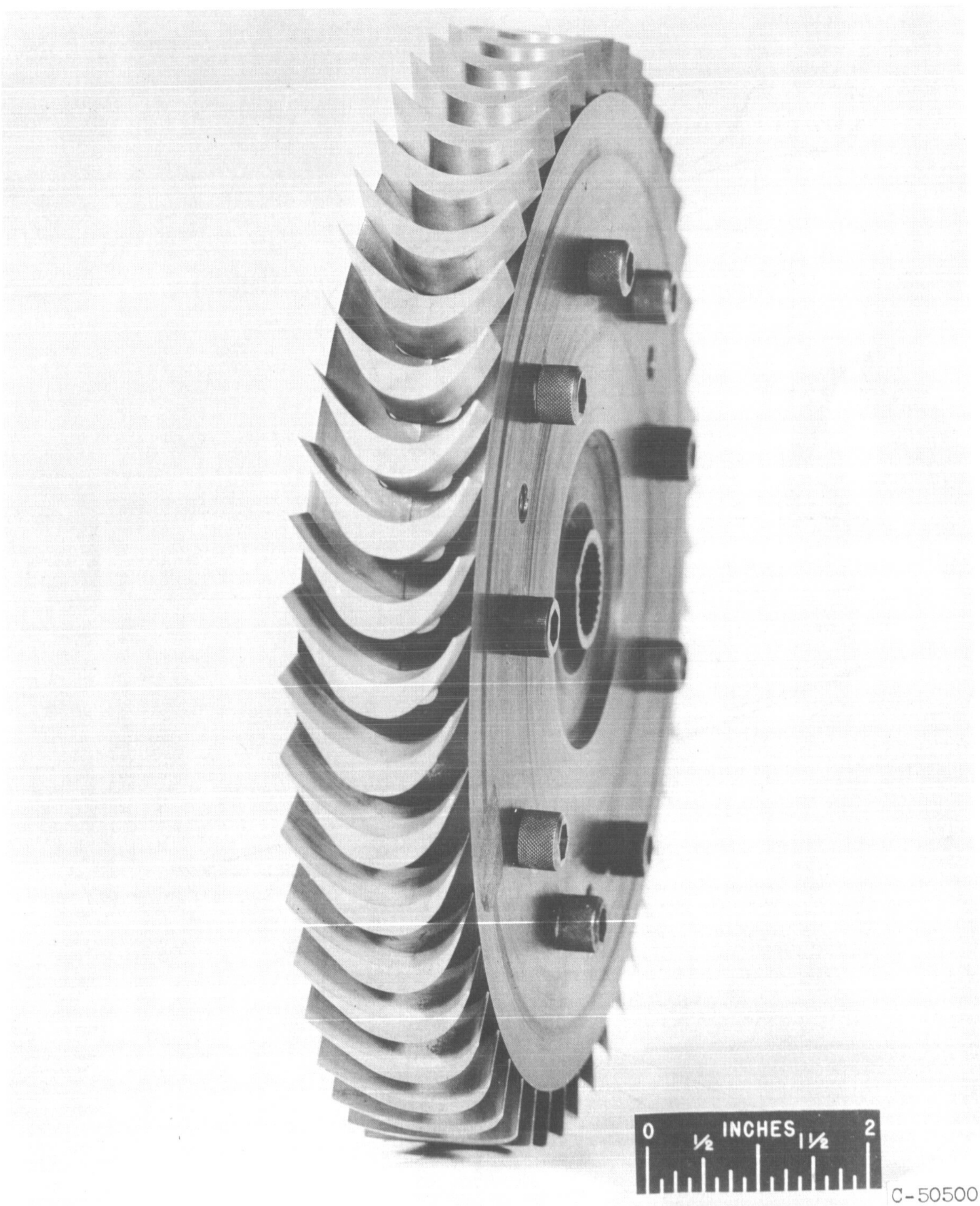


Figure 2. - Turbine rotor.

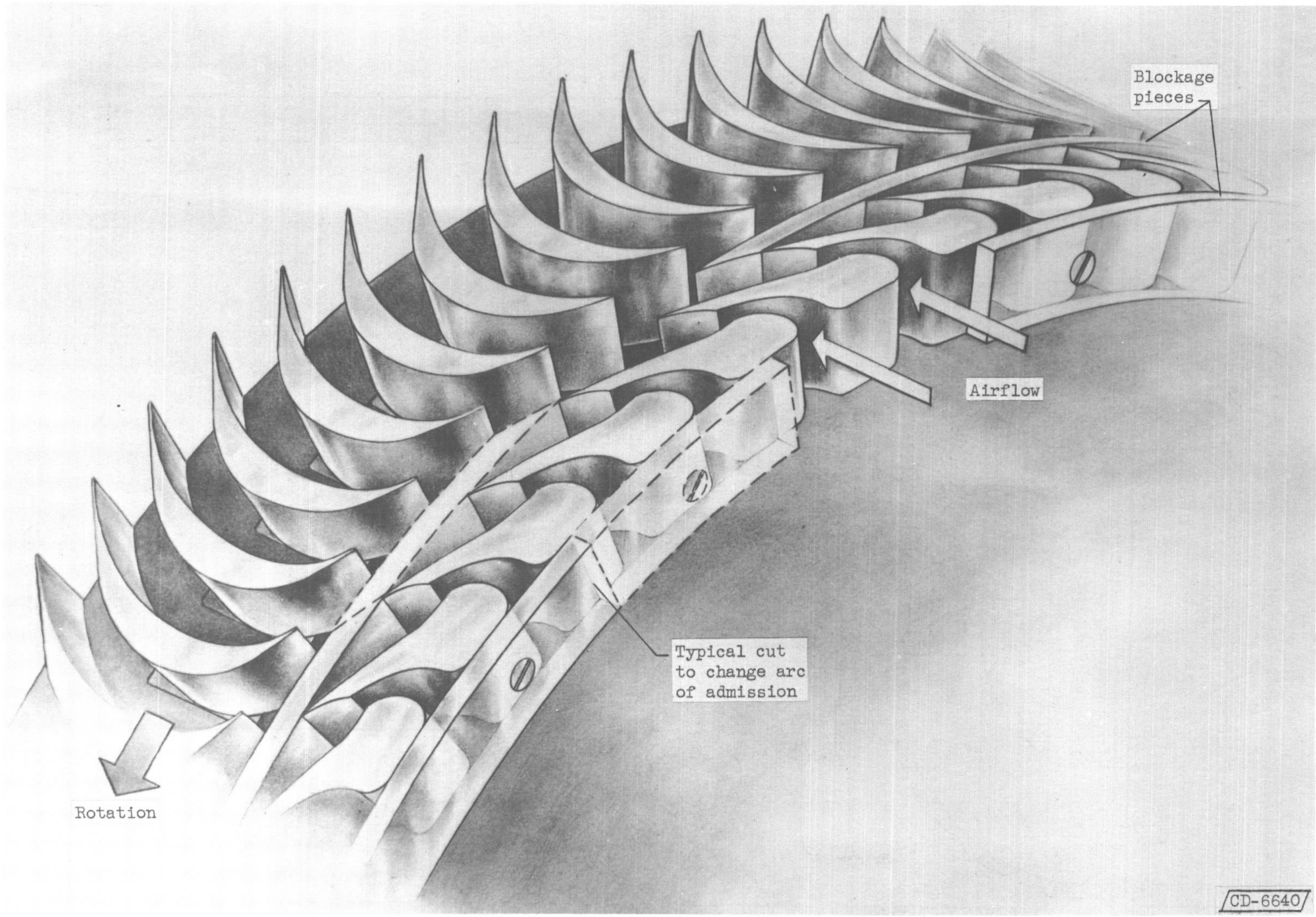


Figure 3. - Method of obtaining partial admission with blockage pieces.

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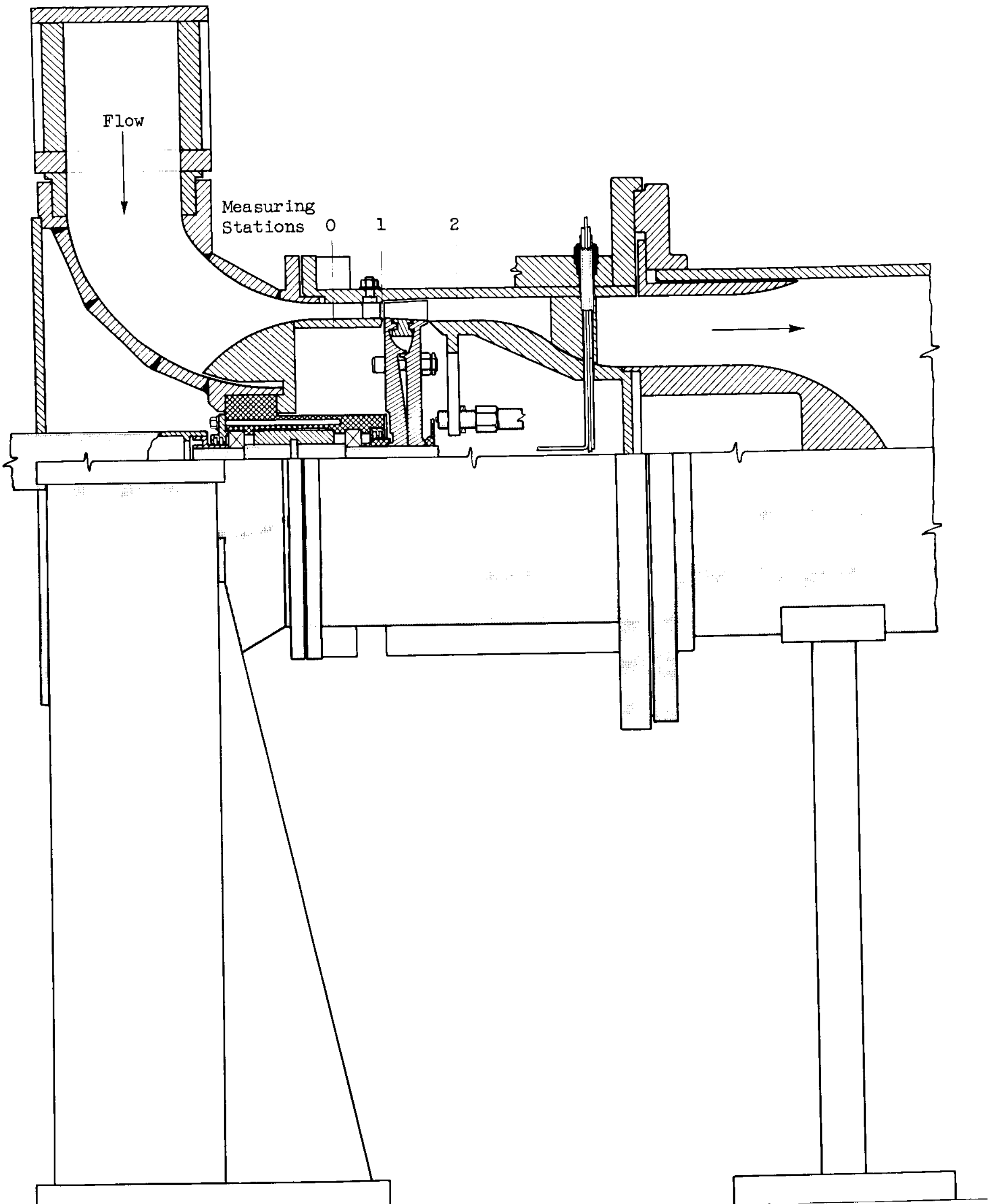


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Figure 4. - Diagramatic sketch of turbine test section.

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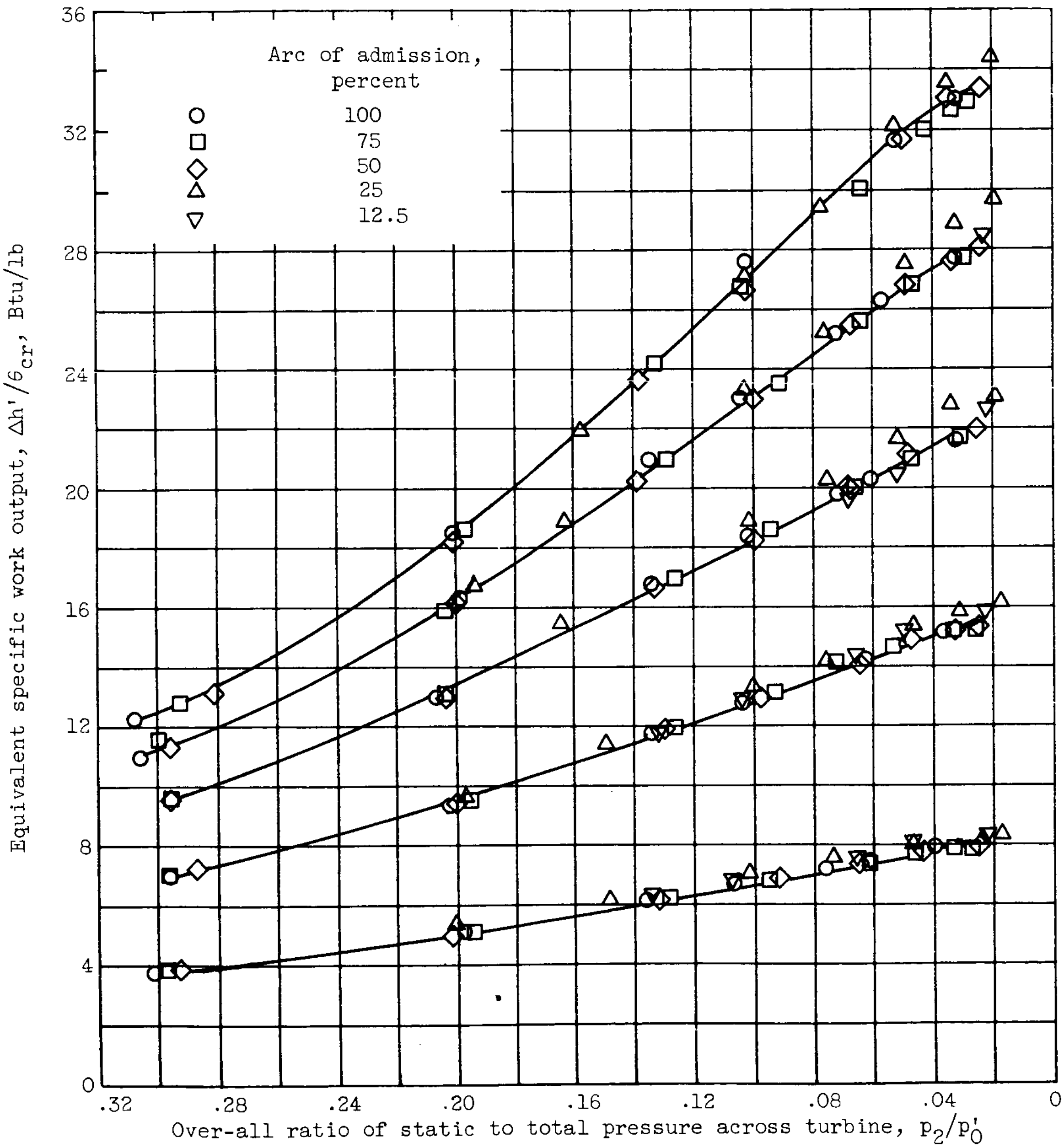


Figure 5. - Effect of partial admission on over-all turbine performance.

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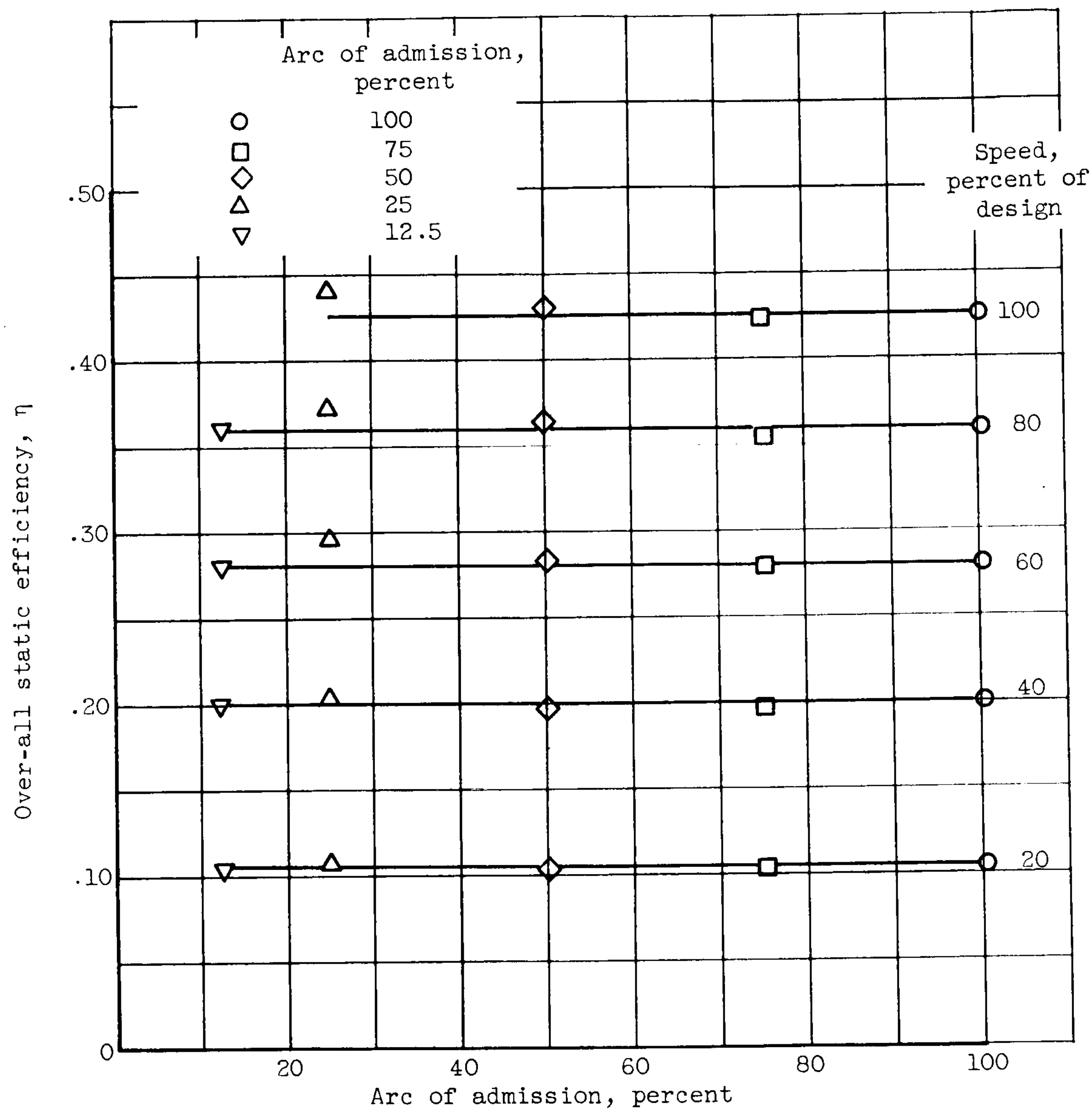


Figure 6. - Effect of partial-admission on turbine over-all static efficiency at design pressure ratio $p_2/p_0'$ of 0.033.

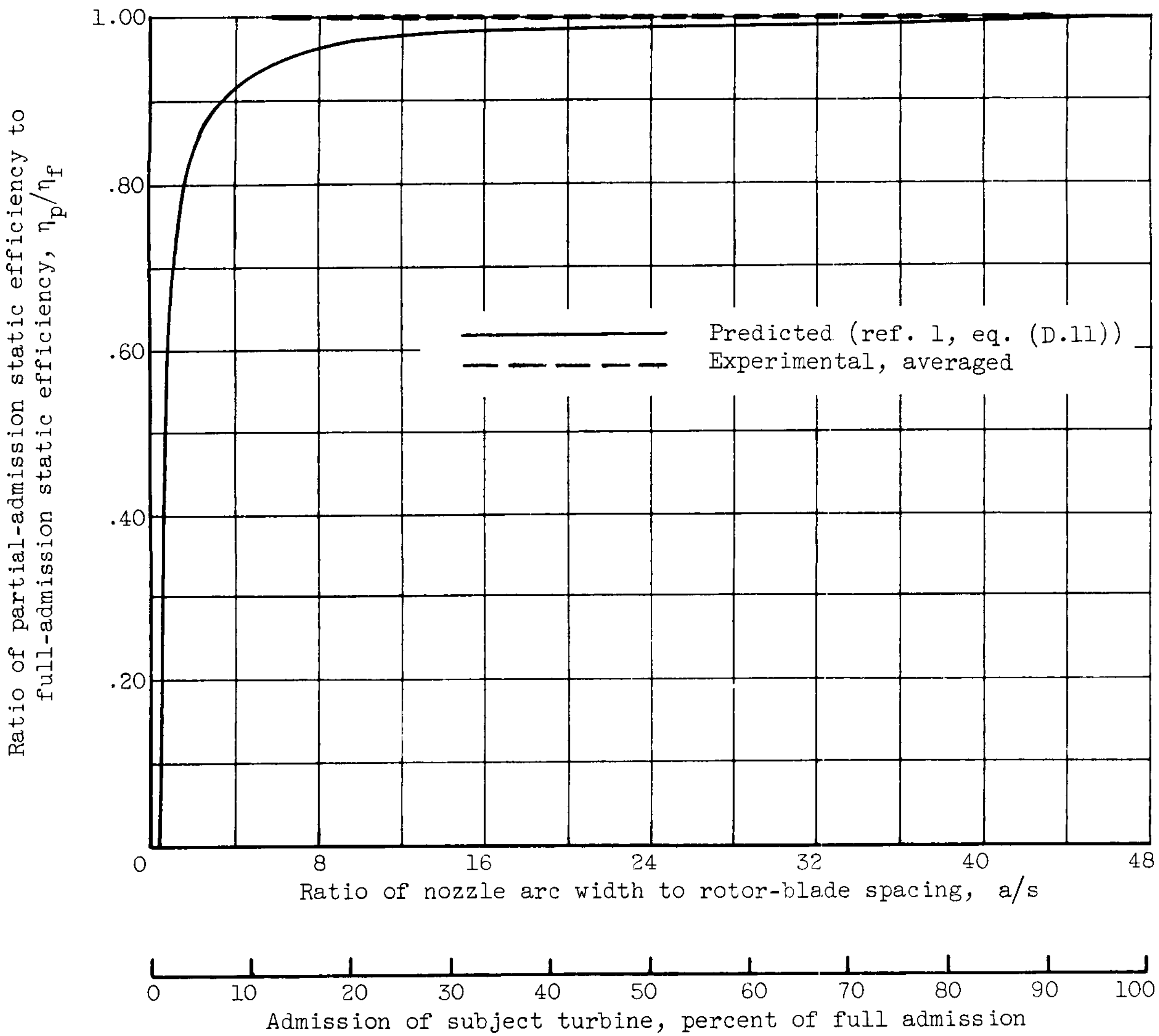


Figure 7. - Comparison of experimental performance with predicted performance of subject turbine at design pressure ratio $p_2/p_0'$ of 0.033.